Radio-over-Fiber Based Architecture to Provide Broadband Internet Access to Train Passengers

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***Abstract*—Nowadays, combining high bandwidth connections (e.g. 5Mbps/user) and fast moving users (e.g. on a train at 300 km/h) while keeping a sufficient level of QoS is still an unsolved bottleneck. In this paper, we propose a cellular trackside solution for providing broadband multimedia services to train passengers. A Radio-over-Fiber network in combination with moving cells forms the base of this realization, and a general optical switching architecture is proposed for implementing the moving cell concept.**

I. INTRODUCTION

To provide the present spectrum of multimedia services (e.g. Video-on-Demand, Online gaming, Voice-over-IP…) to train passengers, an access network characterized by high bandwidth requirements and with a high level of Quality of Service (QoS) is desired. The challenge telecom operators are facing today is to examine how the required bandwidth and quality can be provided to the train carriages.

Therefore, we have designed a dedicated cellular wireless network along the rail tracks. However, most cellular networks in combination with fast moving users, such as train passengers, have one important drawback: the frequent handovers when hopping from one base station (BS) to another cause numerous packet losses strongly reducing the bandwidth. An attractive solution to solve this deficiency could be delivered by an optical access network using Radio-over-Fiber (RoF) [1] to feed the base stations installed along the rail tracks, and this in combination with a "moving cell" concept.

In section II, we motivate the need for this new network architecture and describe the technical challenges. Section III and IV elaborate the optical access network and the moving cell concept, respectively. Finally, in section V, we present a possible optical switching architecture to realize these moving cells in the optical domain.

II. PROBLEM DESCRIPTION

A. Service Requirements

We can assume the broadband connections in a train will approximately follow the connections available at home (nowadays ca. 5 Mbps) with a delay of some years (five years for instance). Considering a double deck train carrying 1500 passengers, an adoption rate of 10% for the Internet on the train service, a required bandwidth of 5 Mbps/user and a statistical multiplexing factor of 20, we need 37.5 Mbps per train. In the distant future, bandwidths of 100 Mbps or even 1 Gbps will also be available at home. To offer this to train passengers while taking into account the above assumptions, a total bandwidth of e.g. 0.75 to 7.5 Gbps / train will be desired. Besides these high bandwidth requirements, several real-time services also require a low latency and jitter, and an uninterrupted network connection.

B. Technical Challenges

The current wireless broadband technologies (e.g. UMTS, HSDPA, WiFi, WiMAX, satellite) are not able to deliverable the above-mentioned service requirements. The bandwidths of most of them (especially UMTS and HSDPA) are too limited, technologies like WiFi and WiMAX cannot cope with high train speeds and a satellite solution experiences an unacceptable end-to-end delay.

In the long term, we believe high-speed Internet connections have to be brought to the train by a dedicated, cellular-based, trackside technology. To increase the data rates, a larger physical bandwidth from the millimeter band can be used, such as the 60 GHz band. However, this high frequency band has two important implications:

- The frequency fluctuation caused by Doppler shifts, which is proportional to the carrier frequency.
- The higher attenuation loss caused by the shorter wavelength and especially for 60 GHz there is a high attenuation increase due to atmospheric oxygen absorption [2].

To solve the first one, the transmission scheme has to be robust against large frequency fluctuations. To overcome these effects, a code division multiplexing (CDM) transmission can be used [3]. The consequence of the second implication is that very small cell sizes (e.g. 100 - 500m), and thus a high amount of base stations, are required. This will involve high investment costs and very-frequent handovers when a train is moving from one base station to another. To illustrate the fast handover rate, assume an intercity train of 160 km/h in combination with a cell size of 100m. This corresponds to one handover every 2.25s. In addition, if the overlap area between two adjacent cells is 10m, the handover must be done within 0.225s. This example proves that a fast and simple handover protocol is indispensable, in contrast to conventional handover times for cellular mobile networks which are typically in the order of e.g. 0.1 to 1s. To reduce the costs, we propose a Radio-over-Fiber (RoF) network (section III), and the handover problem is tackled by means of the so-called moving cell concept (section IV).

III. Radio-over-Fiber (RoF) Architecture

We propose a RoF network to implement a cost-effective solution for a high-bandwidth communications network for train passengers. Next to the network itself, we also discuss the traffic routing and a comparison is made wit a classical solution.

A. RoF Access Network

From the previous section, it turns out a huge number of base stations are required along the railways and combined with e.g. the 60 GHz frequencies, such a dedicated cellular network could be quite expensive. To reduce the associated costs, it would be very interesting to build the base stations along the tracks as cheap as possible. In this case, a RoF network can offer an appropriate solution. A RoF system is a fiber-fed distributed antenna network [1], and its goal is to transfer complicated signal processing functions from the base stations along the railway (in a RoF network indicated as Remote Antenna Units or RAUs) to a centralized control station (CS). The expensive signal processing equipment ((de)modulation, synchronization, multiplexing and spread spectrum techniques, error control...) at the CS can then be shared among several RAUs. To efficiently manage the proposed network, the RAUs are grouped over a distance of e.g. 5 km and then supervised by one CS that feeds all these RAUs via an optical network. As will be explained in more detail in section V, a promising candidate topology to connect all RAUs in the range of one CS is a ring network.

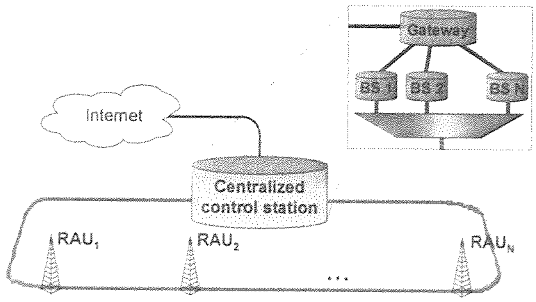

Fig. 1 Radio-over-Fiber network providing Internet on the train

Fig. 1 shows an example of a RoF based cellular network. Several RAUs (RAU_1 to RAU_N) are located along the rail tracks, and an optical ring network interconnects them. All RAUs within the same ring are under supervision of a centralized CS, where all processing is performed. We can also depict this as if the base stations (BSs) themselves are located in the CS, and then connected to each RAU via the RoF network (see Fig. 1). This means the wireless signals transmitted by a BS are not immediately broadcasted into the ether, but firstly, they are carried by an optical fiber to the RAUs, and there, they are put into the ether. Commonly, each RAU is linked with a fixed BS in the CS, and will also have its fixed radio frequency. In section IV, it will be shown that it can be useful to abandon this last property.

B. Traffic Routing

In the downstream direction, the data traffic will be modulated at the right radio frequency in the CS. Then, these radio signals will be converted to the optical domain, and next transmitted by an optical fiber to the RAUs. The latter ones only have to recover the radio signals, which can be immediately transmitted to the train antennas without any further processing. In the upstream direction, the RAUs will capture the whole used frequency band, and this band is transmitted to the CS, where the desired frequencies are filtered out, and further processed.

To get the downstream packets at the right RAU, the CS has to keep track of the train location. This can easily be done by monitoring the upstream packets, coming from the train. The RAU capturing the upstream packets is likely the one situated closest to the train. When the train is moving and the signals are captured by a new RAU, this RAU will soon be the only RAU communicating with the train. The CS can switch the downstream packets to the new RAU almost as soon as when the first packet reaches the CS by using this new RAU. Of course, the CS needs to remember the previous RAU in order to avoid switching back again in the overlap area.

C. Comparison with a Classical Solution

We also stress the difference with a classical cellular wireless network (e.g. the current GSM, UMTS networks), where in the one hand, a base station (Base Transceiver Station or BTS in case of GSM, Node B in case of UMTS) transmits/receives the RF signals to/from the mobile users, and on the other hand, it also processes the RF signals. Now, both functionalities are split up between the RAU and the CS. All intelligence from the BS will be situated at the CS and the RAU can merely be considered as a passive device, and thus becomes significantly simplified, which is a critical issue in these high-frequency systems. Without the simplification of the RAUs, the deployment of micro- or pico- cell networks remains impractical in terms of system installation, operational and maintenance costs. On top of this, system upgrade and adaptation is also made much easier, since the critical equipment is centralized.

D. Related Work

The use of a RoF network combined with millimeter wave band for vehicle communication is also proposed in [3],[4]. Both studies consider this network for road-vehicle communication (RVC) systems instead of train communication. To overcome the huge amount of handovers, the RAUs are grouped in so-called virtual cellular zones (VCZ) and within in one VCZ each RAU uses the same radio frequency. In this way, wile a vehicle is running within a VCZ it does not have to change the RF channel which drastically simplifies the handover scheme. The drawback is that adjacent cells can suffer from co-channel interference (CCI) in the overlap areas. In [3], this is solved by using CDM, while [4] implements a TDMA scheme using separated time slots for different RAUs within one VCZ. It is thus clear that the frequent handovers are a main concern in these networks. In the next section, we tackle this problem by proposing a moving cell concept, which takes into account some typical train characteristics.

IV. Moving Cell Concept

The RoF architecture is mentioned to reduce the investment costs for rolling out a dedicated wireless network, based on a millimeter band technology. In this section, we propose a solution to deal with the fast handovers for a train communication network.

A. *Handovers*

Each time a train antenna exceeds the cell boundary of the RAU to which it is connected at that moment, it has to reconnect to the next RAU, which means a handover has to take place. As already mentioned before, the handover rate will drastically increase when the cell size is reduced to a diameter of e.g. 100 m. It is extremely important to keep the handover times as short as possible (i.e. implementing a fast handover), and handover times in the order of e.g. 100 ms to 1 s are absolutely impermissible. As described in section III, all intelligence is concentrated in the CS, and it is our intention to fully exploit this feature to implement the handovers.

When the train crosses the cell boundary of a RAU, some typical handover actions, briefly summarized below, have to be performed. The purpose of the handover procedure is to move data and control channels of the connection from the RAU and corresponding BS currently communicating with the train (what we call the 'old' RAU/BS) to another RAU (located in another cell) and BS (the 'new' RAU/BS). Usually, by evaluating received measurements from the train, the CS has to decide which cell and related BS/RAU is best suited to keep the connection. Luckily, in the proposed (one-dimensional) network, there is no doubt about the choice of the new RAU: it is simply the next RAU (and associated BS) in the direction the train is moving. The old BS detects the necessity of a handover from the measurements last received from the train. A message containing the 'handover request' is sent to the CS, which prepares the new BS for establishing a connection to the train. Then, the new BS initiates the handover by transmitting the 'handover command' message to the train through the old BS. This step permits the train to locate the radio channel of the new BS/RAU. Upon receipt of the handover command message, the train initiates the establishment of lower layer connections in the new radio channels. In order to establish these connections, the train sends a 'handover burst' message to the new BS and, when successful, transmission is established between the train and the new BS through its RAU. Finally, the train sends the 'handover complete' message to the old BS through the new BS. Upon receiving this message, the old BS releases the old radio channels.

After determining the need for a handover, two important actions have to be executed:

- Preparing the new BS for establishing a connection with the train, and so the data flow has to be processed by this new BS in the CS.
- Establishing lower layer connections in a new radio channel between the train and RAU.

However, in the proposed network architecture, all base stations are grouped in the CS, and normally, only one train will simultaneously be within range of a certain RAU (case of crossing trains will be addressed further in this section). Keeping our mind on these two features, we have proposed the moving cell concept to reduce the handover times.

B. *Moving Cells*

Instead of the train moving along a fixed repeated cell pattern, we consider a cell pattern that moves together with the train (Fig. 2), so that the latter can communicate on the same frequency during the whole connection, also avoiding most, cumbersome, handovers. The idea of moving cells is not completely new, already in [5], there was a proposal with physically moving cells. The idea was rather futuristic, and the operation and maintenance of such a network is also a point of discussion. However, the same principle, now with frequencies moving together with the train, can offer us the opportunity to reduce the handover times. Thanks to the central control system, we can implement these moving cells by reconfiguring the optical network feeding the RAUs. In this way, the speed of the cells can rather easily be synchronized with that of the train, and by means of current optical switching technology, the required reconfiguration time should be kept minimal.

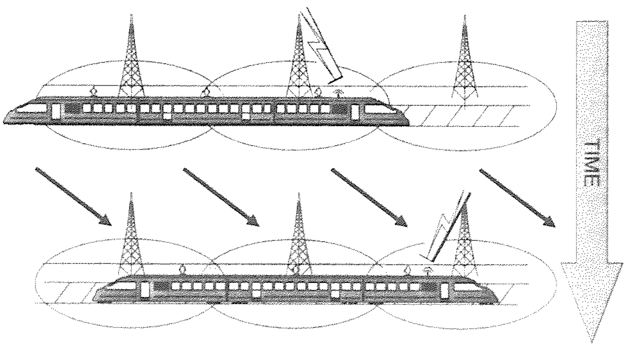

Fig. 2 Illustration of the moving cell concept

We want to stress the moving cell concept is extremely attractive in a train scenario, where a 'burst of users' moves all together at the same speed and follows a predictable route. Besides, only a limited number of RAUs are simultaneously in use. The proposed concept is much less suited for a road-vehicle communication (RVC) system.

By applying the moving cell concept, the actions that have to be performed after determining the need for a handover, will seriously change. The BS before and after the handover remains unchanged, only the used RAU will change. This also means that each BS is no longer associated with a fixed RAU, and besides, the number of BSs can be a lot smaller than the number of RAUs. It is sufficient to equip the CS with as many BSs as train antennas within range of the CS. Furthermore, also the same radio channel will be used, so no new lower layer connections have to be established between the RAU and the train. The only action that has to be executed is that the output of a BS has to be transmitted to another RAU. Simply by an optical switch (see section V), it should be possible to complete the handover. So, no synchronization between the preparation of the new base station and the shift of the radio channel in the connection between the RAU and the train is needed. It is exactly this synchronization that can be very time-consuming, and which is responsible for the fact classical handover times often have an order of magnitude of 1s and the proposed moving cell concept will offer an efficient solution. Note that, so far, we have focused on a future technology with millimeter wave frequencies, but current standards can also be used with RoF (see e.g. [6]), and adapted to implement moving cells.

C. Number of Base Stations

In the previous sections, we have considered the basic situation with only one antenna on the train. For capacity reasons, we can also install two or more antennas, using different radio frequencies, on the roof of a train. In this case, each train is connected to more than one BS at the same time and we have to equip the CS with an adapted switching architecture (see subsection V.B), so all antennas on the train can stay connected with a fixed BS. Several implementations are possible: all antennas connected to their own fixed BS via the same RAU (e.g. a separate antenna for down- and upstream traffic), several antennas spread over the length of the train and connected with their fixed BSs via different RAUs (e.g. each antenna installed on a different carriage) or a combination of both. If one or more BSs are connected to the same RAU, this RAU will transmit several non-interfering frequencies.

Finally, the case with several trains within range of the same CS can be compared with a capacity extension on one train. However, here, we have to make a distinction between trains passing a different RAU and trains simultaneously passing the same RAU. The first situation is very similar to this one with several antennas installed on one train. The biggest difference is that the antennas on different trains will generally not move at the same speed. So, the implementation in the CS will become slightly more difficult. In the other case where two trains pass each other in the same direction (passing trains) or in the opposite direction (crossing trains), two different BSs have to be connected with the same RAU, again transmitting non-interfering frequencies.

V. Optical Switching Architectures

In this section, we propose two general architectures to implement the moving cells in the CS, by using optical switches.

A. General Architecture

First of all, we emphasize that the reconfiguration, needed to implement these moving cells, takes place entirely in the optical domain. Thanks to a ring network, the same fiber can be used by all RAUs within range of the CS and by using Wavelength Division Multiplexing (WDM), each RAU can be associated with a dedicated wavelength. By assigning a fixed wavelength to each RAU, it is possible to efficiently switch the output of a certain BS to another RAU. In this section, we immediately consider the general situation with several antennas within range of the same CS (whether spread over several trains or not). All RAUs within reach of an antenna could then be fed by another radio signal, each delivered by a fixed wavelength.

A possible way to implement the moving cell concept is illustrated in Fig. 3. The intention is to accomplish the moving cells by switching a couple of optical switches in the CS. If in each RAU, there is installed a fixed optical add drop multiplexer (OADM), then in each RAU, a fixed wavelength is terminated. The idea is to put the desired frequency for a certain RAU on the right wavelength by using some optical switches in combination with a WDM laser and external optical modulators (EOMs). Note that for high RF bands (e.g. millimeter waveband) an EOM is required as it is not possible to use direct modulation for frequencies above e.g. 10 GHz [1].

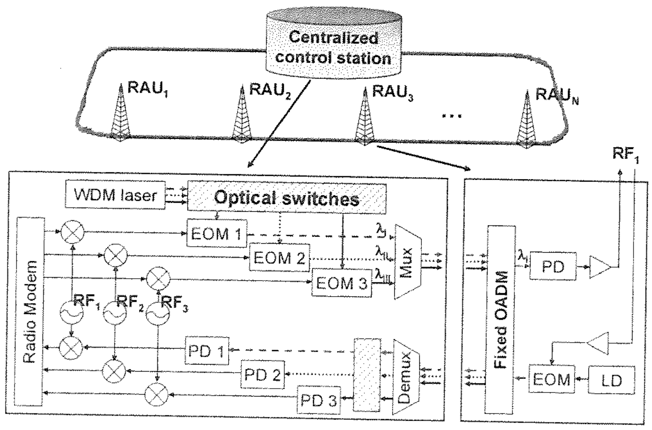

Fig. 3. General architecture to implement moving cells

For the downlink, a base band (BB) radio signal is up-converted to the RF band used for the communication between the RAUs and the connected train antenna. The obtained RF signal is then modulated by an EOM on the wavelength that will be dropped by the fixed OADM of the RAU used at that time (i.e. the RAU within range of the connected train antenna). For this purpose, a beam of light is generated by a WDM laser and sent to an optical switch. To modulate the RF signal on the needed wavelength, this wavelength has to leave the optical switch at the output port connected to the right EOM. The modulated wavelengths leaving the EOMs are multiplexed, and transmitted through the optical fiber to the used RAUs. At the RAUs, a fixed wavelength is dropped and the modulated RF signal is recovered by detecting the optical signal with a photo diode (PD). The recovered RF signal is then amplified and transmitted by the RAU to the antenna on the train. On the example of Fig. 3, three wavelengths are considered, and in the downlink, the output order at the optical switch is λ_I, λ_{II}, λ_{III}. By consequence λ_I is modulated with RF_1, etc. The OADM of the depicted RAU

(RAU_3) drops λ_1, and by this way, RAU_3 is communicating on RF_1 at that time. By reconfiguring the optical switch, it is possible to put RF_1 on e.g. λ_{II} which can be dropped by e.g. RAU_4. So, RF_1 will then be switched from RAU_3 to RAU_4, resulting in a moving cell implementation.

For the uplink, an EOM, located at the RAU, modulates an (amplified) RF signal on the fixed wavelength of the used RAU. This wavelength is locally generated by a laser diode (LD) and after the modulation it is added to the optical fiber by the OADM. The optical signal is passed to the CS where it is demultiplexed and switched to the right PD. Each RF signal is then recovered by a PD, and down-converted to a base band signal.

B. Extended Architecture

Fig. 3 considers three wavelengths and three RF signals, and it is supposed that for every RF signal a different wavelength can be used. As this basic architecture is not generally applicable, we have proposed some extensions.

The number of RF signals (and thus EOMs, corresponding to the BSs from Fig. 1) defines the maximum number of train antennas that can simultaneously be served by one CS. In case of one antenna per train, it is sufficient to equip a CS with as many EOMs as trains within the range of one CS (e.g. four for a CS every 5 km). As mentioned in subsection IV.C, for capacity reasons, it can also be useful to install several antennas on one train, and obviously, the number of EOMs has then to be extended in this way. If the antennas on the same train are physically located together and thus communicating with the same RAU, several RF signals have to be put on the same wavelength, which requires an extension of the optical switching architecture. Note that this situation also occurs if two crossing trains are served by the same RAU. A proposal of an extended architecture is given in Fig. 4. In the given example, RF_1 as well as RF_2 are modulated on λ_1. To realize this extension, in the downlink, some extra optical switches are added, so that a certain wavelength can pass several EOMs. In the uplink, the optical switch has to be able to split an optical signal to more than one PD.

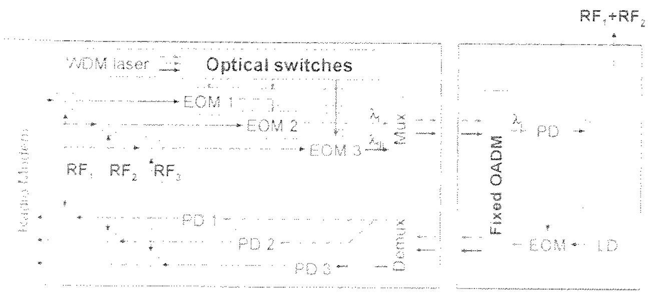

Fig. 4 Extended architecture to implement moving cells

The maximum number of required wavelengths is equal to the number of RAUs per CS, but their amount can be reduced by reusing the same wavelength for different RAUs. However, this means that it is possible that a wavelength is simultaneously used by two or more different RAUs and has to carry several RF signals. This again requires an extended optical switching architecture, comparable to the one shown in Fig. 4.

We want to remark that the architectures in Fig. 3 and Fig. 4 are theoretical proposals. To profoundly evaluate them real-live experiments in a RoF test bed are of utmost importance. Besides, the need for an extended architecture has to be compared with the need for extra capacity on the train, the need to serve crossing trains with the same RAU and the need for reusing the same wavelength for several RAUs.

C. Theoretical Evaluation

The switchover of only some optical switches in the CS will be much less time-consuming than classical handovers. As already mentioned, handover times of 100 ms, 500 ms or 1 s are not an exception. On the other hand, optical switching times in the order of ns or µs are already possible (Table I [7]), and when these switching times correspond to the dominant factor in the handover time, the latter will reduce many orders.

That a handover time of 1 s is not sufficient is already proved in subsection II.B. A cell range of 100 m combined with a train speed of 160 km/h means a handover every 2.25 s, and in combination with a handover time of 1 s, we achieve a loss of 44% (no 7 on Fig. 5), which is unacceptable. As shown on Fig. 5, this loss decreases a lot when using our architecture with optical switches. The numbers on Fig. 5 correspond with the numbers in Table I, and a speed of 160 km/h as well as 300 km/h is depicted. It is obvious the influence of the speed is much smaller than this of the different switching times, which vary several orders of magnitude. Even with Micro-Electro- Mechanical Systems (MEMS) (no 4) the loss is already decreased a lot, and the use of Semiconductor Optical Amplifiers (SOAs, used as switch), electro-optic and acousto-optic switches shows great promise.

TABLE I
SWITCHING TIMES OF SOME OPTICAL SWITCHES [7]

No	switch	switching time
1	SOA, electrooptic	5 ns
2	Acoustooptic	3 µs
3	thermooptic, electro-mechanical, liquid crystal	4 ms
4	MEMS, bubble	10 ms

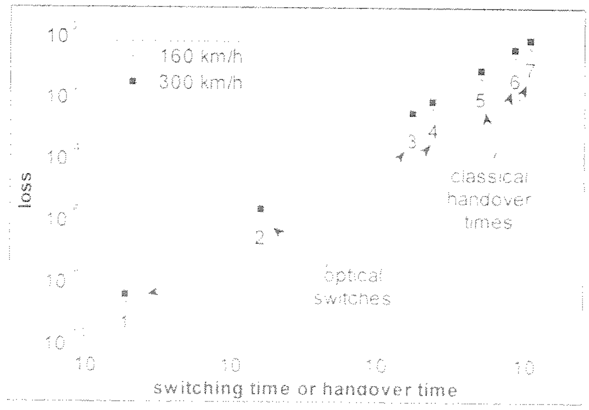

Fig. 5 Some optical switches with switching times and corresponding losses

VI. CONCLUSION

We have proposed a cellular trackside solution to provide broadband Internet access to train passengers. The solution is based on a Radio-over-Fiber (RoF) network to reduce the costs of the remote antenna units (RAUs) along the tracks. Furthermore we have proposed a moving cell concept to limit the handover times when a train moves form one cell to another one. It should be possible to implement the moving cells entirely in the optical domain, and this by some optical switches in the CS of the RoF network. In this way, two optical switching architectures for the control station (CS) are presented.

To provide real broadband access to train passengers, we believe our solution will become very promising in the future. We also want to remark our solution is standard independent. However, to evaluate the general feasibility of the concept and the discussed architectures, a profound validation in a RoF test bed environment is required.

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